



Sustainability of Canada's forestry sector may be compromised by impending climate change

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ABSTRACT

Climate change poses a serious risk to long-term sustainable forest management, particularly when projecting future wood supply for forestry operations. However, few studies have accounted for the cumulative and interacting impacts of climate change on forest productivity and natural disturbances; even fewer have considered drought impacts when projecting wood supply. We modeled how disturbance- and drought-induced tree mortality will affect wood supply in three regions of Canada's boreal forest over a 200-year period under three climate-forcing scenarios. We project strong declines in overall aboveground biomass due to increases in mortality caused mainly by increased drought and wildfire, particularly in drier, western regions. Using two management strategies, we show that maintaining current long-term sustainable harvesting levels will be extremely challenging depending on the level of anthropogenic climate forcing. Increased wildfire activity under severe climate forcing will strongly decrease the availability of harvestable stands. In western areas that are already water-limited, harvesting levels will need to be low to remain sustainable. Our results show that Canada's future wood supply and sustainable forest management practices are highly vulnerable to changes in climate; hence adaptation actions are needed to lower these vulnerabilities.

1. Introduction

Climate change, driven by growing emissions of greenhouse gases (GHG, IPCC, 2014), is affecting the growth and mortality of global vegetation (Allen et al., 2015). This is particularly true within the boreal biome for which temperatures are rising at approximately twice the global average rate (ECCC, 2018). In the boreal forest, the effects of climate change on forests are expected to impact wood supply directly (Kirilenko and Sedjo, 2007; Gauthier et al., 2015b) through significant changes to forest dynamics (i.e., regeneration, growth, and succession) and natural disturbances (Kirilenko and Sedjo, 2007). Whether Canada's forestry sector continues to have a stable supply of merchantable wood in the near and long-term remains an important issue in boreal forest management (Brecka et al., 2018).

Perhaps the most important effect of climate change on the boreal forest will be the influence of moisture availability on forest dynamics

(e.g., Berner et al., 2013; Girardin et al., 2016). In addition to forest growth losses (Price et al., 2013), moisture deficits lower site suitability (D'Orangeville et al., 2016), often increase vulnerability to insects and disease (Jactel et al., 2012), and increase fire frequency (Gauthier et al., 2015b). Increasing drought has already led to regional increases in tree mortality around the world (Allen et al., 2015) and within the boreal forest (Peng et al., 2011). In the coming decades, increased anthropogenic climate forcing is likely to expose large swaths of the boreal forest to increased risk of drought impacts (Aubin et al., 2018; Boucher et al., 2018). Moreover, drought-induced increases in area burned will strongly impact successional pathways by lowering stand age and shifting forest composition towards early succession, broadleaved species (Boulanger et al., 2016), potentially reducing wood supply over large areas (Gauthier et al., 2015a). Although growth and biomass gains may occur in some areas, these gains will be highly dependent on local moisture availability (Girardin et al., 2016). Even in areas where

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1971 - 2000 | Climate moisture index

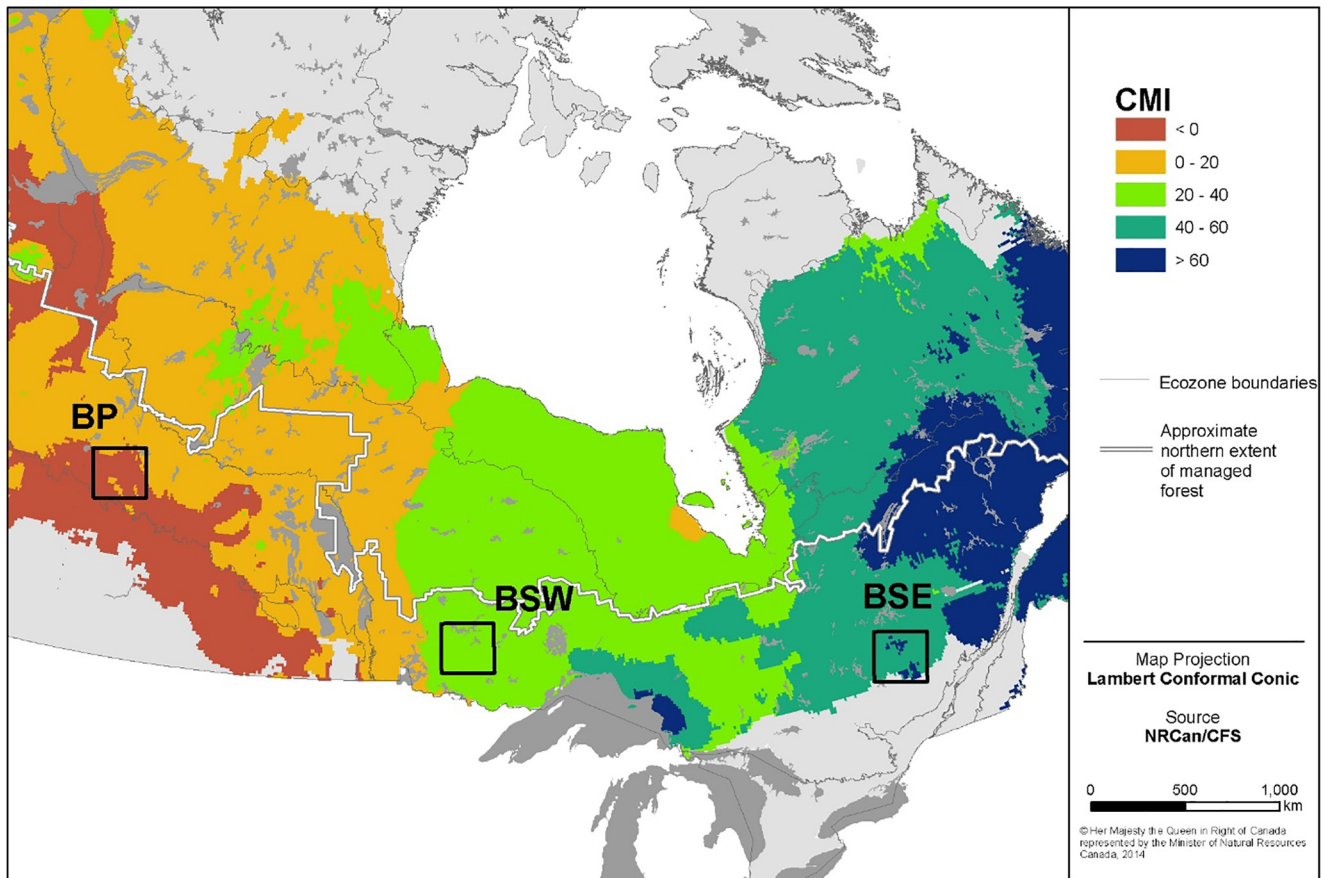


Fig. 1. Location of the simulated study regions (black outlines) as well as ecozone (gray outlines) and the approximate northern boundaries (white outlines) of the managed forest in Canada. The spatial distribution of the Climate Moisture Index (CMI) (Hogg, 1997) within the boreal forest is also shown. CMI is calculated as the difference between annual precipitation and potential evapotranspiration following (Hogg, 1997). Wet or moist conditions are indicated by a positive CMI value and imply that precipitation is sufficient to support closed-canopy forests.

growth is projected to increase, increased losses due to natural disturbances may lead to net decreases in wood supply (Girardin et al., 2012; Chen and Luo, 2015) as was reported for central and western Canada over five decades (Chen and Luo, 2015). In addition, increases in temperature are projected to decrease the abilities of boreal tree species, e.g., balsam fir, black and white spruces, larch, to compete with temperate species (e.g., maples, oaks), many of which are of high commercial importance (Reich et al., 2015; Boulanger et al., 2016; Boulanger et al., 2017; D'Orangeville et al., 2016).

The combined negative effects of climate change on overall boreal tree biomass will pose considerable challenges for the forestry sector. One direct outcome is an overall decrease in the availability of harvestable stands and extracted wood volumes (Brecka et al., 2018). High-value coniferous species would be most affected, potentially triggering short- to long-term shortages in wood supply, notably for the construction industry (McKenney et al., 2016; Wood et al., 2016). In this context, decreasing annual harvest volumes might help maintain a smaller but stable wood supply (Savage et al., 2010; Creutzburg et al., 2017). Indeed, since harvest and climate-induced impacts on forest landscapes are cumulative (Boucher et al., 2018), maintaining current harvesting rates in a changing climate might overwhelm the capacity of the forest to provide sustainable wood volume (Gauthier et al., 2015a,b). In addition, reducing annual harvest levels might also help in maintaining key attributes of the ecosystem (Daniel et al., 2017). However, the extent to which changes in harvest rates have to be modified to fulfill these objectives remains a challenging and

contentious question.

In Canada's boreal forest, there is a strong east–west gradient of declining annual moisture availability that is likely to persist as climate change alters future precipitation regimes, making dry regions even drier (IPCC, 2014). As such, drought-induced changes in wood supply are likely to be strongly influenced by such gradients, with western regions being most at risk (Boulanger et al., 2016). Despite the potential adverse consequences of climate change, many modeling studies suggest increases in future commercial wood supply are possible due to rising atmospheric CO₂ concentration and longer, warmer, growing seasons (e.g., Kellomäki et al., 2008; Lutz et al., 2013). However, many of these studies (both globally and within the boreal) do not explicitly incorporate natural disturbances or stand-level ecological processes that are affected by climate change (McKenney et al., 2016; Tian et al., 2016). There is no doubt that natural disturbances are strongly linked to forest landscape dynamics and wood supply, particularly in the boreal forest (Gauthier et al., 2015a). It is therefore essential to simulate the impacts of disturbances on wood supply, and how these are likely to change in a warming climate. Wood supply modeling studies generally fail to account for dynamic changes in forest composition triggered by natural disturbance and harvest activities. As such, these models potentially overestimate projected wood supply. Hence, we advocate these interacting impacts be fully acknowledged and assessed in a holistic approach. To date, few studies have been conducted from this perspective (NRTEE, 2011; McKenzie et al., 2016).

In this study, we investigate how climate change will affect wood

Table 1
LANDIS-II input data for tree species simulated within the three study regions.

Species	Species code	Study region*	Longevity	Age at maturity	Shade tolerance†	Effective seed dispersal (m)‡	Maximum seed dispersal (m)	Vegetative regeneration	Post-fire regeneration	Growth curve shape parameter	Mortality curve shape parameter
<i>Abies balsamea</i>	ABIE.BAL	BSE, BSW	150	30	5	25	160	No	Seeding	0	25
<i>Acer rubrum</i>	ACER.RUB	BSE	150	10	3	100	200	Yes	Resprout	0	25
<i>Acer saccharum</i>	ACER.SAH	BSE	300	40	5	100	200	Yes	Resprout	1	15
<i>Betula alleghaniensis</i>	BETU.ALL	BSE	300	40	3	100	400	Yes	Resprout	1	15
<i>Betula papyrifera</i>	BETU.PAP	All	150	20	2	200	5000	Yes	Resprout	0	25
<i>Fagus grandifolia</i>	FAGU.GRA	BSE	250	40	5	30	3000	Yes	Seeding	1	15
<i>Larix laricina</i>	LARI.LAR	All	150	40	1	50	200	No	Seeding	0	25
<i>Picea glauca</i>	PICE.GLA	All	200	30	3	100	303	No	Seeding	1	15
<i>Picea mariana</i>	PICE.MAR	All	200	30	4	80	200	No	Serotiny	1	15
<i>Picea rubens</i>	PICE.RUB	BSE	300	30	4	100	303	No	Seeding	1	15
<i>Pinus banksiana</i>	PINU.BAN	All	150	20	1	100	100	No	Serotiny	0	25
<i>Pinus resinosa</i>	PINU.RES	BSE, BSW	200	40	2	12	275	No	Seeding	1	15
<i>Pinus strobus</i>	PINU.STR	BSE, BSW	300	20	3	100	250	No	Seeding	1	15
<i>Populus balsamifera</i>	POPU.BAL	BSW, BP	130	20	1	1000	5000	Yes	Resprout	0	25
<i>Populus tremuloides</i>	POPU.TRE	All	150	20	1	1000	5000	Yes	Resprout	0	25
<i>Thuja occidentalis</i>	THUJ.OCC	BSE, BSW	300	30	5	45	60	No	Seeding	1	15
<i>Tsuga canadensis</i>	TSUG.CAN	BSE	300	60	5	30	100	No	Seeding	1	15

**From neighboring cells.

* See Fig. 1 for study region names.

† Index of the ability of species to establish under varying light levels where 1 is the least shade tolerant and 5 is the most shade tolerant.

‡ Distance within which 95% of seeds disperse.

supply from Canada's boreal forest. Our analysis takes into account the cumulative and interacting impacts of climate change on: drought, landscape-level natural disturbances such as fire and insects, stand-level ecological processes including tree growth, regeneration, mortality and competition, as well as the direct effects of harvesting on forest biomass. Such a modeling approach allows for a more realistic and holistic assessment of large-scale variations in future wood supply than many previous studies.

2. Methods

2.1. Study regions

We simulated forest landscape dynamics within three study regions located at the transition between boreal and hemiboreal zones in each of three forested ecozones in Canada ([Ecological Stratification Working Group, 1996](#)). These ecozones are, from west to east, the Boreal Plains (BP), the Boreal Shield West (BSW) and the Boreal Shield East (BSE) ([Fig. 1](#)). These study regions are located along a strong moisture gradient as expressed using the [Hogg \(1997\)](#) annual climate moisture index (CMI) for the 1971–2000 period, with the BP being the driest region ($CMI < 0$ cm) and the BSE the wettest ($CMI > 40$ cm). The three study regions encompass a wide variety of forest types, soils, and local climates, and differing natural disturbance regimes (see ([Boulanger et al., 2016](#)) for further details). Harvest occurs at various rates within these regions, with the highest clearcutting rates occurring in the BSE during the 2002–2011 period ([Guindon et al., 2014](#)).

2.2. Climate data

Monthly time series of current climate were interpolated from climate station records using the data of [McKenney et al. \(2013\)](#). Future climate projections were obtained for the Canadian Earth System Model version 2 (CanESM2) using data downloaded from the World Climate Research Program (WCRP) Climate Model Intercomparison Project Phase 5 (CMIP5) archive for each of three different radiative forcing scenarios, known as Representative Concentration Pathways (RCP, e.g., [van Vuuren et al., 2011](#)), namely RCP 2.6, RCP 4.5 and RCP 8.5. The RCP 2.6 scenario represents a situation where radiative forcing peaks at $\sim 3 \text{ W m}^{-2}$ before 2100 and then declines to reach 2.6 W m^{-2} by 2100. In the RCP 4.5 scenario, radiative forcing is assumed to stabilize at 4.5 W m^{-2} after 2100 without an “overshoot” pathway. Conversely, in the RCP 8.5 scenario, the forcing reaches 8.5 W m^{-2} in 2100 and continues to increase for an unspecified period afterwards. Using these forcing scenarios, the CanESM2 projects mean annual temperature increases of 3.5°C (RCP 2.6) to 7.5°C (RCP 8.5) throughout the southern boreal region by 2100 (compared to circa 2000), while average precipitation is projected to increase by 10 to 25%, with relatively small differences among forcing scenarios. Data from CanESM2 for the 1900–2100 period were bias-corrected by expressing them as differences from (temperature) or ratios of (precipitation) to the CanESM2 monthly means for the 1961–1990 period.

2.3. LANDIS-II forest landscape simulation model

LANDIS-II is a spatially-explicit raster-based forest landscape model that simulates disturbances, seed dispersal, and forest succession ([Scheller et al., 2007](#)). Species are defined using unique life-history attributes and are represented in each grid cell as 10-year age-cohorts. Cell resolution was set to 250 m (6.25 ha). Forest composition and structure in each cell were initialized using forest properties data derived from the Canadian National Forest Inventory (NFI) and cohort data from provincial permanent and temporary forest inventory plots (FIP). Using species' biomass, as well as mean annual temperature and total annual precipitation as variables, we performed a nearest neighbor spectral analysis to attribute the FIP showing the smallest

Euclidean distance to each 250 m cell. This imputation was conducted on a 20-yr age class basis to ensure that the Euclidean distance between FIP and the 250 m cell was mostly attributable to site productivity rather than stand age. Each of these cells was then assigned to a spatial unit (i.e., “landtype”) with soil (Mansuy et al., 2014) and climate conditions considered homogeneous over the spatial unit. Grid cells with more than 50% of their area covered with non-forest cover types were classified as inactive.

2.4. Forest succession and species growth potential

Forest succession in each grid cell was simulated using the LANDIS-II Biomass Succession extension v 3.1 (Scheller and Mladenoff, 2004). This extension takes into account tree species’ cohort age, life-history traits, and species-specific landtype responses, and simulates changes in cohort biomass over time as each cohort regenerates, ages and dies. Species’ life-history traits information was collected from various sources and previous LANDIS-II publications including several previous studies involving LANDIS-II for North American forest landscapes (Table 1).

In the LANDIS-II Biomass Succession Extension, three sets of dynamics inputs have to be calibrated in order to make species-specific growth and reproduction sensitive to soil and climate conditions. These parameters are the (i) species establishment probabilities (*SEP*), (ii) maximum possible aboveground net primary productivity (*maxANPP*), and (iii) maximum aboveground biomass (*maxAGB*). Unlike, e.g., PnET-Succession, the Biomass Succession is not an ecophysiological model per se so it has to be first calibrated outside the LANDIS framework. One of the most common ways to calibrate the dynamic growth and reproduction inputs when using the Biomass Succession extension is to scale-up outputs from a climate- and soil-sensitive forest gap/patch model. We parameterized our LANDIS-II simulation experiment with the individual tree-based, forest patch model, PICUS version 1.5 (Lexer and Honninger, 2001; Taylor et al. 2017). PICUS simulates the dynamics of individual trees on 10 × 10 m patches across forest stand areas (generally 100–1000 patches, corresponding to total areas of 1–10 ha). It accounts for spatially explicit interactions among patches via a 3D light module and simulates seed dispersal explicitly, as well as the effects of climate and soil properties on tree population dynamics (Lexer and Honninger, 2001). Used individual tree information from

the NFI and provincial FIPs, we parameterized PICUS for 17 tree species occurring in the study regions (Table 2). To be included, each tree species had to contribute at least 0.3% of total AGB of a given study region according to the 2001 NFI forest properties maps at 250 m resolution (Beaudoin et al., 2014). A complete description of the model and how it was parameterized and validated can be found in Taylor et al. (2017).

Using PICUS, we simulated mono-specific 1-ha stands for each of the leading tree species. A factorial simulation design was used to simulate all mono-specific stands for each study region, tree species and landtype, under climate conditions for specific periods (2000–2010, 2011–2040, 2041–2070, 2071–2200) and forcing scenarios (baseline, RCP 2.6, RCP 4.5, RCP 8.5). All stands were simulated for 300 years from bare-ground and used local soil (Mansuy et al., 2014) and interpolated climate time-series data. Values for *SEP*, *maxANPP* and *maxAGB* were then derived from these simulations (see Boulanger et al. (2016) for computational details). *maxBiomass* was computed as the average value after a given amount of time (typically 100 or 150 years). The maximum 10-yr smoothed instant (yearly) biomass increment computed from PICUS is used as *maxANPP*. For *SEP*, we assumed that it was directly linked with the time necessary to accumulate aboveground biomass in PICUS. We took the time necessary to accumulate aboveground biomass (*t*) in PICUS and considered it as the result of a random process associated with an annual probability of $1/t$. We thus considered the establishment of a cohort as a Bernoulli trial conducted every year during a time step. As the timestep used in our simulation was 10 years, we computed *SEP* as the probability of having more than zero successes (1 or more) in 10 consecutive trials.

Pixel-level simulations were conducted for one specific landtype chosen subjectively from the most common landtypes in a given study region to represent one general type of ecosystem (e.g., softwood boreal forest, mixedwood temperate forests, etc.). The successional pathways resulting from 1000-year simulations (Boulanger et al., 2016) showed good agreement with those reported in the literature (e.g., Cyr 2014).

2.5. Forest harvest

Forest harvest was simulated using the Biomass Harvest extension (v3.0; Gustafson et al. 2000). Mean harvested patch size and total harvested area were summarized by forest management units (FMU).

Table 2

Select input parameters specific to PICUS for species simulated within the three study areas.

Species	Soil nitrogen*	Minimum soil pH [†]	Maximum soil pH [†]	Minimum GDD (Base temp 5 °C) [‡]	Maximum GDD (Base temp 5 °C) [‡]	Maximum SMI [§]	Optimum SMI [§]
ABIE.BAL	2	2	9	150	2723	0.3	0
ACER.RUB	2	2	9.5	500	6608	0.5	0.05
ACER.SAH	2	1.7	9.9	450	5093	0.3	0
BETU.ALL	2	2	10	500	4517	0.5	0.05
BETU.PAP	2	2.2	9.4	150	3081	0.5	0.05
FAGU.GRA	2	2.1	9	500	5602	0.7	0.1
LAR.LAR	1	3	9.6	150	2548	0.3	0
PICE.GLA	3	2	10.2	150	2495	0.5	0.05
PICE.MAR	2	2	8.5	150	2495	0.3	0
PICE.RUB	2	2	7.8	450	3239	0.3	0
PINU.BAN	1	2.5	10.2	300	3188	0.7	0.1
PINU.RES	1	2.5	8	500	3300	0.7	0.1
PINU.STR	2	2	9.3	500	4261	0.7	0.1
POPU.BAL	2	2.3	11	150	3024	0.5	0.05
POPU.TRE	2	2.3	11	150	3024	0.5	0.05
THUJ.OCC	2	3	10	500	3383	0.7	0.1
TSUG.CAN	2	2.2	9	500	4660	0.5	0.05

* Nitrogen response curves: Three classes (1–3) with 1 being very tolerant.

[†] USDA plant fact sheets (USDA and NRCS (2016)) and the Ontario Silvics Manual (OMNR, 2000) were used to derive the widest optimum pH range possible.

[‡] Growing Degree Days (GDD). We used McKenney et al. (2011) growing season model, specifically the minimum GDD for the 0 °C growing season window with degree days over 5 °C. For the maximum GDD, we used GDD Maximum from McKenney’s previous growing season model (McKenney et al. 2007).

[§] Soil Moisture Index (SMI). Determines each species tolerance to drought (see Lexer and Honninger pg. 52). HighTolerance (0.1–0.7), MedTolerance (0.05–0.5), LowTolerance (0–0.3).

For simplicity, only clearcut logging was simulated, as this is most frequently practiced in the study regions. Only stands comprised of cohorts older than 60 years were allowed to be harvested. Stands meeting this criteria were randomly selected for harvesting. Harvesting was assumed to progress to neighboring stands until patch size reached 150 ha, or until there were no other neighboring stands qualifying for harvesting within the patch. To simulate clearcutting, all cohorts within each harvested patch were removed except for the 0 – 10 year age cohort. Harvesting proceeded within each FMU until a specified annual harvest area was reached, depending on the simulation scenario. Two harvesting scenarios were simulated: low-intensity clearcutting (*Low harvest* – clearcutting applied to 0.4% of the area per year); and clear-cutting with an intensity similar to current management practices (*Baseline harvest* – clearcutting applied to 0.8% of the area per year). Harvest rates were held constant throughout the simulations unless not enough stands qualified for harvesting. In this latter case, harvesting proceeded until there was no more stands available.

2.6. Natural disturbances

Two natural disturbance agents, namely fire, and spruce budworm (SBW, *Choristoneura fumiferana* [Clem.]) outbreaks, were considered in the LANDIS-II simulations. Both disturbance agents are recognized to have major impacts on Canada's boreal forest landscapes (e.g., Volney and Hirsch, 2005). Historically SBW has accounted for the majority of areas disturbed by insects in the study regions). Fire simulations were conducted using the LANDIS-II Base Fire extension, which simulates stochastic fire events dependent upon fire ignition, initiation and spread. Fire regime data (annual area burned, fire occurrence, and mean fire size) were summarized into "fire regions" corresponding to the intersection of each region and the Canadian Homogeneous Fire Regime (HFR) zones of Boulanger et al. (2014). Baseline and future fire regime parameters within each fire region were calibrated according to models developed by Boulanger et al. (2014) and further updated for different RCP scenarios (Gauthier et al., 2015b).

SBW outbreaks were simulated using the Biological Disturbance Agent (BDA) extension v3.0 (Sturtevant et al., 2004), which is specifically designed to simulate host tree mortality following insect outbreaks. Host tree species for SBW included, from the most to least vulnerable, balsam fir (*Abies balsamea*), and white (*Picea glauca*), red (*P. rubens*) and black (*P. mariana*) spruces (Hennigar et al. 2008). Outbreaks are simulated as probabilistic events at the cell level with probabilities being a function of the site and neighborhood resource dominance (e.g., host species occurrence within a 1-km radius) as well as regional outbreak status. Outbreak impacts (tree mortality) are contingent on these probabilities as well as on host species- and age-specific susceptibility. Parameters used in this study were calibrated and validated using various sources for the boreal and hemi-boreal forests (MacLean, 1980; Hennigar et al., 2008). Regional outbreaks were calibrated at the highest severity level possible using this extension and were set to last at most one-time step (10 years) and to occur every 40 years in accordance with typical observed regional recurrence cycles (Boulanger et al., 2012).

Drought-induced mortality was simulated by first modeling species- and ecozone-specific mortality curves related to CMI. Species-specific mortality was retrieved from undisturbed FIP located within each ecozone. Species-specific generalized linear mixed effect models (GLMM) were developed to predict annual mortality rates according to CMI values, while taking into account FIP stand age as well as the FIP itself as a random factor. We deemed the annual resolution of the model adequate to capture and project most of the drought-related mortality occurring in our study area (Hogg, 1997). Using the same climate datasets described above, we projected future CMI values for each 30-year period and all landtypes using each climate forcing scenario. Future species-specific drought-related mortality was projected using future annual CMI values as input to each species GLMM. Projected drought-

related, species-specific mortality was summed for each decade and was then included in the LANDIS-II simulations by removing biomass accordingly over the 10-yr timestep period using the Biomass Harvest extension. Drought-induced mortality in each timestep was applied equally to all tree age cohorts.

2.7. Simulation design

Simulations were run under four climate projections, (corresponding to baseline, and the RCP 2.6, RCP 4.5 and RCP 8.5 radiative forcing scenarios) and two harvest scenarios. For each harvest and climate change scenario combination, five replicates were run for 200 years, starting in the year 2000, using 10-year time steps. Except for scenarios involving the baseline climate, fire regime parameters were allowed to change in 2010, 2040, and 2070 according to the average climate corresponding to each forcing scenario; fire regime parameters for 2070 were held constant for the remainder of the simulations (to 2200). Dynamic growth and establishment parameters (SEP, maxANPP and maxAGB), as well as drought-induced mortality, were allowed to change according to each climate scenario following the same schedule used for the fire regime parameters.

2.8. Analyses

Aboveground biomass (AGB) simulated by LANDIS-II was used as a proxy for wood supply. We first assessed climate change impacts on total and species-specific AGB simulated for the baseline (0.8% yr⁻¹) harvest scenario under each anthropogenic climate forcing. Drought- and fire-specific biomass losses, i.e., the biomass killed by the disturbance relative to the total biomass of the pixel, were compiled as well as for biomass harvested. To estimate the impacts of climate change on harvest sustainability, we then computed temporal trends in harvested biomass and potential harvestable biomass under the two harvest scenarios. Potential harvestable biomass corresponds to the total biomass occurring in stands older than merchantable age, i.e., 60 years old. It then includes biomass that was harvested. Finally, we estimated trends in the proportion of conifer biomass in harvestable stands. For all these parameters, variation among replicates caused by model stochasticity was very small over the spatial extent of the study regions so we present averages of each set of five replicates. Results were lumped by study regions.

3. Results

3.1. Climate change-induced AGB fluctuations

Simulated total regional AGB decreased strongly in response to increasing climate forcing in all regions (Fig. 2). Declines in AGB were most extreme under the RCP 8.5 scenario, especially for the drier BSW and BP study regions, with major declines taking place after 2070 (Fig. 2). Among the three study regions, temporal changes in AGB were least dramatic in the BSE, but this region still experienced a 33% loss in AGB under RCP 8.5. Only in the BSE, under less severe climate forcing (RCP 2.6, RCP 4.5), did total AGB remain relatively stable over the 200 year simulation period.

Strong declines in total AGB mostly resulted from sharp decreases in biomass of commercial conifer species, with declines being most pronounced under RCP 8.5 in every study area (Fig. 2). Black and white spruces, as well as balsam fir, declined sharply in all regions, but most notably in the BSW and BP under RCP 8.5. Moreover, although being the most abundant conifer in the BSW, jack pine declined considerably throughout the simulation period, especially under RCP 8.5. As a result, most of the future biomass was comprised of less economically important broadleaved species (e.g., trembling aspen, white birch, maples) throughout the three study regions under RCP 8.5.

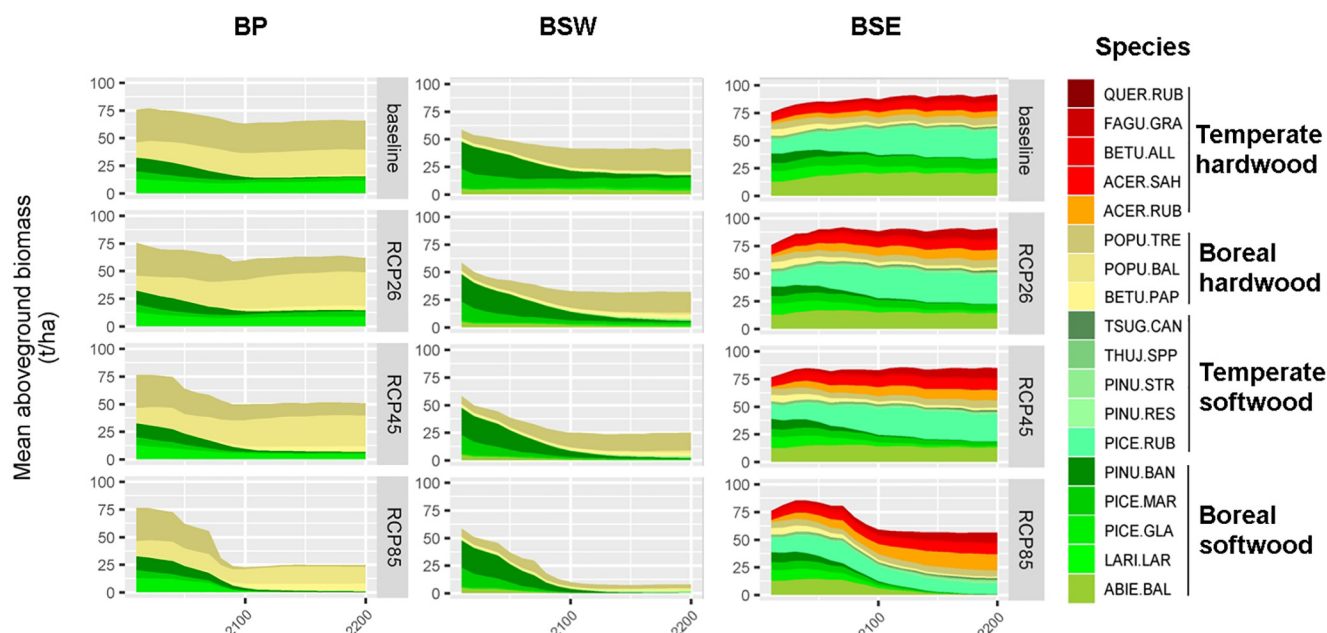


Fig. 2. Stacked trends in species aboveground biomass for each of the three regions simulated under either baseline, RCP 2.6, RCP 4.5 or RCP 8.5 climate scenarios. See Table 1 for species abbreviations. Species are stacked according to hardwood/softwood as well as according to their general distribution (boreal vs temperate).

3.2. Projected drought- and fire-related tree mortality

Drought conditions were projected to increase significantly in all regions with increasing climate forcing. CMI decreased steadily, by 5–12 cm (under RCP 2.6) and 12–20 cm (under RCP 8.5) compared with CMI predicted for current climate (Fig. 3).

In response to increased simulated drought, drought- and fire-induced tree biomass loss increased, but mostly under RCP 8.5 and after 2070 (Fig. 4). Drought-related losses in AGB were more important than simulated biomass losses due to fire and harvesting under all climate

scenarios in BP and BSE. For the BSW, fire-related biomass loss was most important (Fig. 4). Projected fire- and drought-related biomass losses increased as a function of anthropogenic climate forcing and were greatest under RCP 8.5 in the BSW and BP. In the BP, for instance, simulated total biomass losses due to drought and fire relative to total biomass increased to ca 30% by 2100 under RCP 8.5, which almost doubled the initial rate of biomass loss simulated for the beginning of the simulation (i.e., approximately 15 to 20%). Large increases were also projected for the BSW, where biomass loss reached 35% per decade under RCP 8.5, increasing from 15% in 2000. Although much lower in

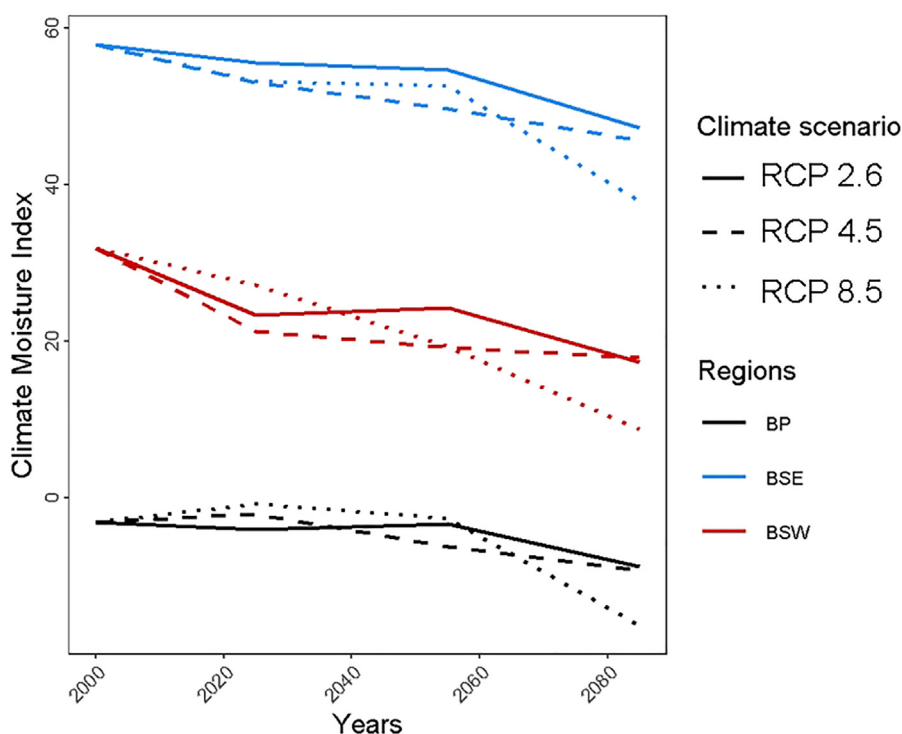


Fig. 3. Trends in climate moisture index (as averaged over 30-yr periods) in the three study regions under the three different anthropogenic climate forcing scenarios.

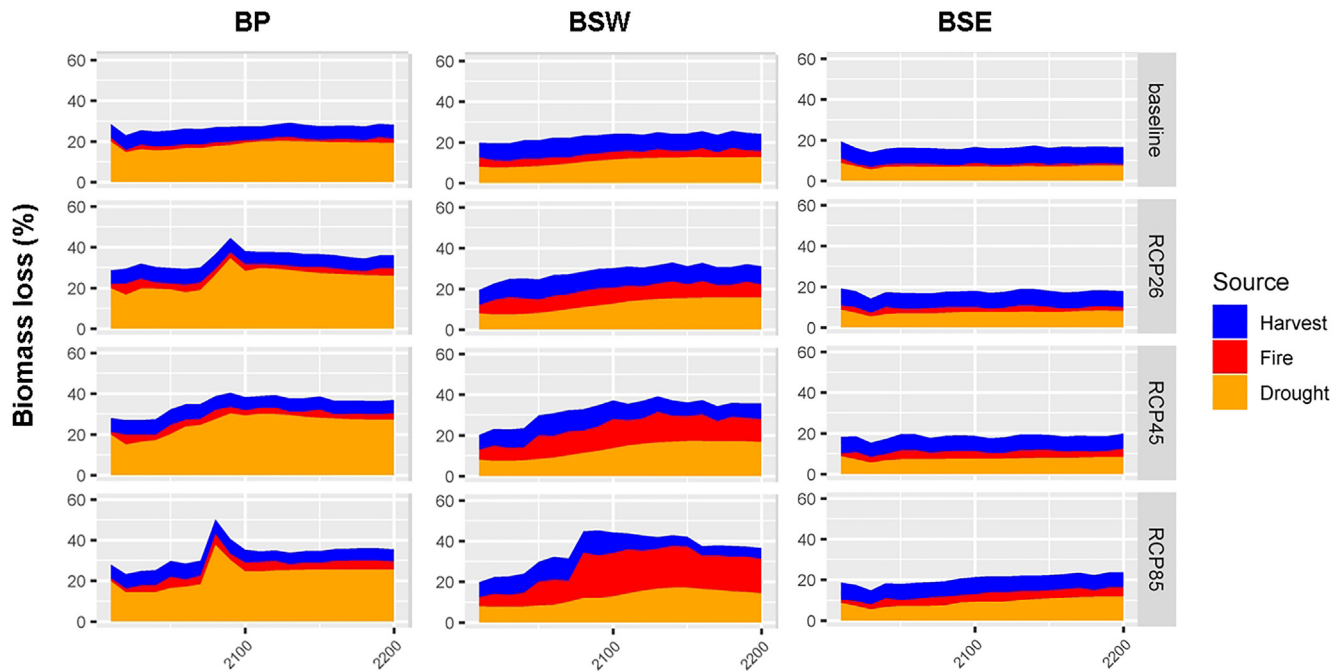


Fig. 4. Trends in the proportion of total biomass loss by drought, fire and harvest in the three study regions under the four climate scenarios.

the BSE, drought- and fire-related biomass losses were projected to double (8% per decade in 2000 vs 16% per decade in 2100) under the most severe climate forcing scenario.

3.3. Impacts on harvestable biomass and harvest

The simulated consequence of increasing losses of AGB was that the forested area available for harvesting decreased substantially with increasing climate forcing (Fig. 5A). Relative to baseline climate,

harvestable area decreased by 10–30% and 22–70% by 2200, under RCP 2.6 and RCP 8.5, respectively. The largest losses occurred in the BSW, where fire activity increased the most.

Increased climate forcing reduced harvestable conifer biomass disproportionately compared to its impact on overall conifer biomass, (Fig. 5B). Impacts were most pronounced under RCP 8.5 in the BP and BSW, where harvestable biomass decreased by approximately 90% after 2100, compared to 70% for the BSE. Under RCP 2.6, declines in harvestable conifer biomass were smaller for the BSE and BP (10–15% reductions). Lowering the simulated target harvesting rate (from 0.8% to 0.4% per year) reduced these declines under RCP 2.6 in the BSW and under RCP 8.5 in the BSE.

Large losses in harvestable biomass were reflected in total biomass and area harvested, especially under RCP 8.5 (Fig. 6). Declines in biomass harvested accelerated after 2050 and reached 45% to as much as 85% after 2100 under RCP 8.5 for the BSE and BSW, respectively. Conversely, under RCP 2.6, harvested biomass was similar or slightly lower than that simulated under the baseline climate scenario. Large decreases in area harvested in all regions after 2050 show that simulations failed to reach the targeted area for harvest with increased climate forcing (Fig. 6B).

As expected, decreasing the area targeted for harvesting (from 0.8% yr^{-1} to 0.4% yr^{-1}) compensated for much of the loss in available biomass and actual area harvested due to increased climate forcing. When compared with similar harvesting scenarios under baseline climate, biomass harvested at the high harvesting rate would be reduced by half in the BSW under the RCP 2.6 and RCP 4.5 climate scenarios, whereas at the low harvesting rate, biomass harvested annually would be relatively unaffected (Fig. 6A). Comparable results were found for actual areas harvested (Fig. 6B). In the BSE, declines in area harvested, relative to baseline, were three times smaller under the low harvest scenario compared with the high harvest scenario, regardless of climate forcing. Under RCP 8.5 however, decreases in both area and biomass harvested were rather similar between both harvesting scenarios in the BSW and BP regions. As might be expected, these results imply that wood supply will be more sustainable at lower harvest levels, as the climate becomes generally warmer and drier.

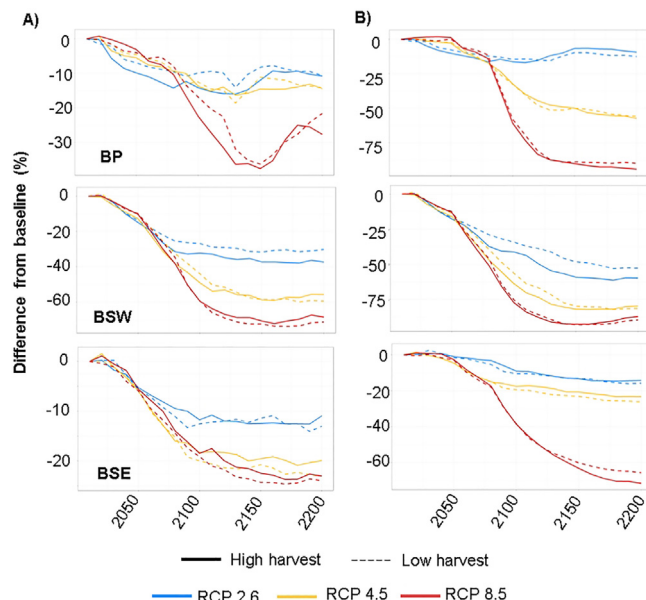


Fig. 5. Simulated changes in total (A) and conifer (B) forest biomass classified as harvestable (> 60 years old) under the three anthropogenic climate forcing scenarios. Differences (generally decreases) are expressed as percentages relative to harvested biomass under the baseline climate scenario and the same harvesting scenario (percent of total area harvested annually). High (solid) and low (dashed) harvest scenarios are both illustrated in each of the three study regions.

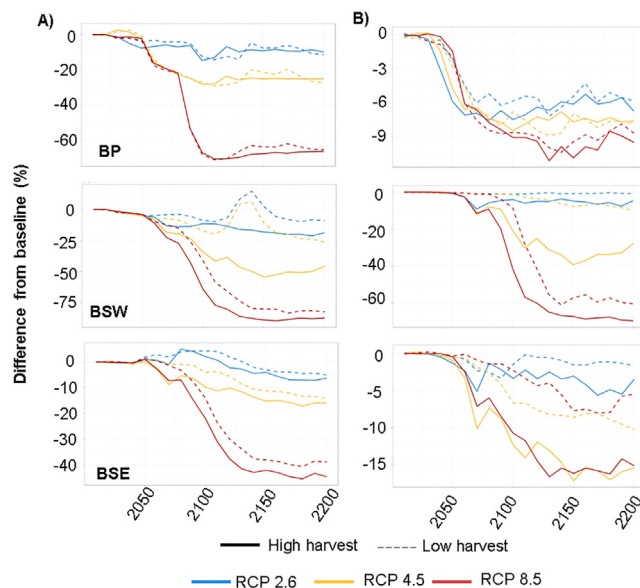


Fig. 6. Simulated changes in harvested biomass (A) and harvested area (B) under the three anthropogenic climate forcing scenarios. Differences from baseline (generally decreases) are expressed as percentages *relative to the baseline scenario, under the same harvesting scenarios*. High (solid) and low (dashed) harvest scenarios are both illustrated in each of the three study regions.

4. Discussion

Under increasing anthropogenic climate forcing, our simulations projected steady declines in timber resources that were consistent among regions, climate scenarios and across most boreal commercial tree species. These declines coincided with general increases in tree mortality (through fire or drought) which exceeded projected AGB accumulation, severely influencing overall harvest levels. Further, our simulations indicated that most major changes are likely to occur before 2100 (~2050–2080). This suggests there is a high likelihood that sustainable wood supply will not be maintainable in these boreal regions for more than a few decades in the 21st century, unless significant action is taken to reduce GHG emissions and prevent further warming.

Our climate scenario data show that, currently, drier regions are likely to become much drier in the near future, which would in turn, greatly reduce the availability of harvestable forest biomass. As a corollary, the more eastern BSE ecozone appears generally less prone to drought effects, compared to the western BSW and BP ecozones, but the BSE is still very likely to experience economically significant declines in harvestable timber under RCP 8.5. Climate conditions under the RCP 8.5 forcing will become seriously detrimental to primary productivity and biomass in all regions, leading to major declines in harvestable wood, as forecasted in previous studies (Charney et al., 2016; McKenney et al., 2016; Aubin et al., 2018; Dyderski et al., 2018). The largest threat to forest resources in the BSW appears to be from fire, whereas drought would likely play a larger role in the BP region. Both fire (Gauthier et al., 2015b; Daniel et al., 2017) and drought-related boreal tree mortality (Michaelian et al., 2011; Peng et al., 2011; Hogg et al., 2017) would have the potential to reduce boreal wood supply considerably. Our estimates of a potential decrease in harvestable stands due to the general decrease in average forest age provide further evidence that large increases in fire activity would require major changes to harvesting practices to preserve the long-term sustainable wood supply (Vijayakumar et al., 2016; Boulanger et al., 2017).

Our simulations also indicate that wood supply from broadleaved deciduous species will be less reduced than that from coniferous species throughout each region. Shifts in the relative abundances of conifers and broadleaved species have been observed (Fisichelli et al., 2014) and

projected (Evans and Brown, 2017; Taylor et al., 2017) for other areas along North America's southern boreal regions. Increased fire frequency, especially in the BSW and BP, would likely favour trembling aspen, balsam poplar and white birch, at the expense of late-successional boreal conifer species which are much less tolerant of short fire return intervals, under severe climate forcing (Boulanger et al., 2016; Whitman et al., 2019). This agrees with field studies that suggest deciduous broadleaved pioneer species, such as trembling aspen, have been increasing in abundance in the western boreal in recent decades (Johnstone et al., 2010; Searle and Chen, 2017), due to post-fire vegetative reproduction and dispersal of wind-adapted buoyant seeds over much greater distances than typically achieved by conifer seed (see Table 1). In addition to increased drought- and fire-related mortality, decreases in harvested biomass could also result from significant declines in growth rates, mostly affecting conifers. In fact, boreal conifer species decline might arise from two situations. In the eastern regions of Canada, declines in growth and regeneration potential of conifers reduces their ability to compete against mesophytic deciduous species (Reich et al., 2015). This competition process could lead to rapid changes in forest composition (Boulanger et al., 2016). Conversely, in the central and western regions where boreal conifer species are predominant, declines in growth and regeneration potential will contribute directly to important declines in overall stand biomass, as there is little potential for immediate replacement by other tree species adapted to warmer/drier conditions. In the first case, shifts towards greater abundance of broadleaves suggest mixed wood forests will become more prevalent, along with an apparent northern shift in the boreal-temperate zone as climate warming proceeds (Fisichelli et al., 2014; Evans and Brown, 2017). In the second case, in the absence of warm-, dry- and/or disturbance-adapted species, our results suggest that overall declines in conifer biomass would lead closed boreal forest to transition to more open parklands—likely dominated by aspen—in drier landscapes (Stralberg et al., 2018) with very low harvestable timber content.

Our simulations indicated that reducing long-term harvesting targets may be necessary to ensure steady, sustainable wood supply when faced with declining biomass due to the multiple impacts of climate change on forest productivity, species composition and losses due to droughts and fires. Indeed, harvest levels declined in both harvest scenarios, but the declines were much less severe, in relative terms, when a lower harvesting intensity was assumed. As shown by Raulier et al. (2014), maintaining a stock of timber could buffer the effects of unexpected stand-killing disturbance events on regional wood supplies. For example, reduced harvesting should allow for additional biomass accumulation and contribute to other forest ecosystem services (e.g., carbon sequestration, biodiversity). That said, warming comparable to the RCP 8.5 scenario appears likely to reduce harvest levels to the limits of operability in some regions, given present-day harvesting practices. Such results suggest an urgent need to explore adaptation options sufficient to maintain a viable forest industry in Canada's southern boreal forests under a "worst-case" GHG forcing scenario. Although intended to explore an unlikely high-risk future, recent analyses suggest that the RCP 8.5 pathway becomes increasingly improbable (Hausfather et al., 2020). That said, if high harvest levels were maintained and global GHG emissions were to approximate the RCP 8.5 trajectory, the simulated likely increase in areas lost to fire and drought could drive a potential collapse of wood harvesting in some regions of Canada's southern boreal forests.

Implications for the forest industry are potentially significant. Our results show that finding sustainable, mature harvestable wood supplies will become increasingly difficult in the most drought-prone regions of Canada's southern boreal forests (particularly under extreme climate warming scenarios). Declines in harvestable conifer biomass could have serious economic implications as conifers are generally preferred by industry. Such compositional shifts will influence the type and quality of wood products that companies can manufacture (Boulanger et al.,

2017; Brecka et al., 2018). If regionally unsuitable for specific wood products, a greater prevalence of mixed-wood forests containing broadleaved trees may necessitate innovation towards utilizing less desirable species or towards intensive management of desired species. Furthermore, lower productivity in conifer stands would likely increase costs to harvest less profitable, low-volume stands, depending on available markets, or cause wood supply shortages (e.g., McKenney et al., 2016; Yemshanov et al., 2018). Hence, serious impacts on the supply value chain are to be expected (Ireland et al., 2001; Williamson et al., 2009; Gauthier et al., 2015a). These climate-induced decreases in wood supply, particularly from coniferous stands, are likely to influence forest product market price and consumer preferences, which in turn would both impact the economic welfare of consumers and producers (McCarl et al., 2000; Albrecht et al., 2010).

We acknowledge that our study bears some limitations. First, it is important to recognize that LANDIS-II is not a timber supply optimization model. As such, the harvesting regimes simulated in our study are not intended to represent optimal solutions under the tested climate change scenarios. Also, for the sake of simplicity, we did not account for the fact that harvesting decisions could differ between coniferous and deciduous stands, but instead gave them equal weights when selecting stands to harvest. If we had weighted conifer stands more heavily, the resulting decreases in harvestable biomass under increasing anthropogenic climate forcing might have been even greater. As such, the different simulated harvesting scenarios might be viewed as “what if” scenarios testing for harvesting level impacts. Moreover, our drought-mortality model is rather simplistic and does not account for interaction between climate and any stand characteristics (other than species composition) or soil characteristics. It rather projects average but tractable impacts of future drought conditions on stand mortality and hence on timber supply.

Despite these limitations, this study provides insight into possible changes in harvestable AGB with important implications for boreal forestry (Boulanger et al., 2016; Boulanger et al., 2018). In addition to stand-scale processes, here we show the importance of including landscape-scale natural disturbances, such as drought and fire, in wood supply modeling. Disturbances are a major driver of biomass dynamics in the boreal forest but are not commonly modeled in wood supply studies (Kellomäki et al., 1997; Gauthier et al., 2015b; McKenney et al., 2016; Nordstrom et al., 2016). Using landscape-scale models that capture drought-related mortality, wildfire, and process-based interspecific competition, it should become possible to make better long-term management decisions for alternative projections of anthropogenic climate forcing. Sustainable forest management will likely require more careful planning, particularly in areas likely to be exposed to increased threats. Indeed, new adaptation options to alleviate declines in harvest yields are needed urgently. From our analyses, we argue that reduced harvesting intensity, and maintaining timber reserves to buffer against high mortality events is key to maintaining timber supplies, especially under low to medium anthropogenic climate forcing. Other management options not explored in this study should also be considered. These include planting to accelerate stand establishment following harvesting or natural disturbance, and assisted migration to allow climate-resilient genotypes and species to keep up with shifts in their optimal climate zones, notably within their CMI envelope (see Halosky et al., 2018 for a review). We suggest prompt decision-making is urgently needed to introduce significant actions aimed at mitigating impacts of climate change on Canada's forests and forest industry. Notably, review of regional harvesting levels is one area where changes made in the near future could bring significant long-term improvements in wood supply.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

H.Y.H.C., C.S., A.B., Y.B and A.R.T. conceived the study; A.B., Y.B., E.B.S. and A.R.T. conducted data synthesis and analysis; All authors contributed to writing the manuscript.

Declaration of Competing interest

No conflicts of interest to declare.

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